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Chaff and Jamming Effectiveness Simulator for Anti-ship Cruise Missile Engagement: Validation and Application (U)

John M. Ozard, Jay Johnson and Jamie Wong
Defence Research Establishment Ottawa

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA

TECHNICAL MEMORANDUM
DREO TM 1999-061
June 1999

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Electronic Countermeasures Techniques Group
Electronic Countermeasures Section

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ABSTRACT

The two-dimensional chaff and jamming effectiveness simulator for anti-ship cruise missile engagements, Chaff and Jamming Anti-Ship Cruise Missile (CJASCM), is currently under development under a Defence Industrial Research (DIR) contract. CJASCM was rapidly prototyped in the fifth generation language Simulink which itself is built on Matlab and is therefore modular and open to modification to a few missiles on few ships from the present one missile on one ship simulation. DREO provided Beta testing of CJASCM as agreed under the DIR contract and carried out the limited validation described here. Numerous simulations of chaff effectiveness as a function of chaff position, missile heading and wind heading, confirmed that the simulations followed the conceptual model as summarised in this document and that the code was robust. The present simulation can be used for illustrative purposes and after further development and end-to-end validation could be used for training and for investigating ways of identifying chaff decoy tactics. In order to use the code for developing precise electronic warfare tactics for a one-on one engagement, further development and validation of the overall simulation and of the modules comprising the simulation will be required. Enhancements, such as conversion to three-dimensions and the inclusion of a relational database to archive simulation input and output, are already planned in the time remaining under the Defence Industrial Grant (DIRG). At the completion of the present DIRG further development and validation will be required if CJASCM is to be used for tactics generation. The extent of these enhancements will depend on the scenarios under investigation. On account of the open nature of the software, extension to new countermeasures equipment and missiles should remain feasible.

RÉSUMÉ

La conception du simulateur bidimensionnel de leurrage et brouillage pour les engagements de missiles de croisière antinavire – missile de croisière antinavire de leurrage et de brouillage (MCANLB) – est en cours, en vertu d'un contrat avec Recherche industrielle pour la défense (RID). Le MCANLB est rapidement passé au stade de prototype selon le langage de simulation de cinquième génération Simulink qui, étant issu de Matlab, est modulaire et se prête à des modifications pour des missiles embarqués sur quelques navires aux fins de la présente simulation (un missile par navire). Le CRDO a réalisé les essais bêta du MCANLB en vertu du contrat avec RID, ainsi que la validation limitée décrite ci-dessous. Plusieurs simulations d'efficacité des leurres, selon leur position, le cap du missile et la direction du vent, ont confirmé que les simulations ont respecté le modèle conceptuel résumé dans le présent document et que le code est robuste. La présente simulation peut servir à des fins d'illustration et, après d'autres travaux de conception, à offrir la formation et trouver des façons de détecter les tactiques de leurrage. Pour utiliser le code en vue d'élaborer des tactiques de guerre électronique nécessaires dans les engagements un contre un, il faudra valider et élaborer la simulation dans son ensemble et les modules, dont ceux de simulation. Des améliorations comme la conversion tridimensionnelle et l'inclusion d'une base relationnelle de données d'entrée et de sortie de simulation sont prévues pour la fin de la subvention de RID. À la fin de la présente subvention, d'autres travaux de conception et de validation seront nécessaires si le MCANLB doit servir à l'élaboration de tactiques. L'ampleur de ces améliorations dépendra des scénarios étudiés. Compte tenu de la nature ouverte du logiciel, son application à du matériel de contre-mesures et à des missiles nouveaux devrait être possible.

EXECUTIVE SUMMARY

CJASCM, a member of a suite of electronic warfare simulators, is a two dimensional simulator for anti-ship cruise missile engagements that models chaff and jamming effectiveness. CJASCM offers the possibility of affordable training for Electronic Warfare (EW) operators in EW concepts for the Canadian Navy. CJASCM also has the potential for use in developing EW tactics and as a host for prototyping algorithms for Electronic Warfare Control Processors.

This document summarises the result of a preliminary assessment of CJASCM for modelling the terminal phase of an engagement. Version 1.2/1.3 of CJASCM's underlying conceptual model, predictions for chaff effectiveness and limitations are described.

The present simulation approximates the engagement as two-dimensional. This restricts the software to a missile that is altitude stabilised in the terminal phase. The simulator is based on modelling the most significant features of a missile to achieve sufficient fidelity. Generic or specific possibly classified, parameter values may be input for a simulation. For the terminal phase of an engagement, the missile, ship, chaff, jammer, and radar propagation models are sufficient to capture the essence of EW for training purposes. Some modules in CJASCM also have sufficient fidelity for identifying methods for finding or designing robust EW techniques.

During the assessment the code was executed in excess of 100,000 times without a crash attributable to the code which attests to the code's robustness. Simulation of a typical engagement without displays required 25,000 million clock cycles so that the simulation took at least twice as long as real time on a 450 MHz PC. With display of the missile position and electronic parameters enabled the execution time was doubled.

Since CJASCM is written in the fifth generation language Simulink, which itself is built on Matlab, it is modular and open to modification. The present one-on-one simulation could be developed into a few-on-few simulation. In order to have a faster than real time simulation, a compilation for each new configuration chosen would be necessary. In contrast recompilation for each configuration is not required for open architecture simulations in a third generation language. Not recompiling for new configurations probably carries a cost in execution time and memory requirements.

Numerous simulations of chaff effectiveness as a function of chaff position, missile heading and wind heading, confirmed that the simulations followed the conceptual model as summarised in this document. At the commencement of the DIR contract CJASCM did not have sufficient fidelity for tactics generation. In order to use the code for developing precise electronic warfare tactics for a one-on-one engagement, further development and validation of the overall simulation and of the missile, ship, chaff, jammer and propagation modules will still be necessary at the completion of this DIR. Amongst other things an adequate database and user interface for setting up multiple engagements for ranges of parameter values as well as a variety of realistic missile, sensor, and weapons modules will be required.

To reduce simulation time by an order of magnitude automatic conversion from Simulink to C is under investigation. Enhancements to CJASCM, such as conversion of the propagation model and seeker lobe pattern to 3-D as well as the inclusion of a relational database to archive simulation input and output for multiple engagements, are already planned in the time remaining under the DIR.

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1.0 INTRODUCTION

The purpose of this document is to describe the result of an assessment of Version 1.2 of the two-dimensional simulator for countermeasure effectiveness, Chaff and Jamming Anti-Ship Cruise Missile (CJASCM). During the validation a correction to the code was required to produce correct simulation results and the new version was labelled Version 1.3. All results presented were recalculated using Version 1.3.

Tactical Technologies Incorporated (TTI) developed CJASCM under a Defence Industrial Research (DIR) grant where at most 50% [1] of the funding came directly from the Defence Research and Development Branch (DRDB). In 1997, TTI submitted the proposal [2] to support the research and development of a computer-based simulation and analysis tool for the assessment of Electronic Countermeasures (ECM). This development was to build on experience at TTI and to meet a need for inexpensive simulation models for ECM scenarios. Support for such simulations arises from four needs. First, it stems from the need to find cost-effective ways to assess the effectiveness of ECM for the protection of military ships and military aircraft. The second need is that of planning the most efficient and beneficial field trials. Third, other models, both more and less sophisticated, may be compared to CJASCM as part of a validation process for all of the models. When the software is further enhanced it will also be well suited for training Electronic Warfare (EW) operators in the use of and results to be expected from EW tactics.

The confidence assessment methodology employed in this assessment is adapted from the concepts and procedures described in Simulation Validation published by IEEE [3]. The procedure outlined in the Simulation Validation document was chosen to guide the assessment process because it is based on the methodology developed for and resulting from numerous successful assessments.

The level of assessment chosen was driven by a trade-off between resources and the purpose of the assessment. Assessment of CJASCM is carried out in order to validate the code, i.e. to give the user the appropriate level of confidence in the applicability of the code for the stated purpose. The developer intended that the code be used for investigating concepts and tactics. Providing that the code is appropriate for its stated purpose, then it is the user's responsibility to ensure that the stated purpose meets their needs. Risk areas or limitations of the code for its stated purpose that were encountered during the assessment are also identified.

The background to CJASCM described briefly above is followed by descriptions of the scope of the assessment, the assessment approach and the CJASCM model. In the description of the scope the justification for the level of assessment chosen is given. Findings from the assessment and risk areas are described with the description of each model component. A summary of the result of validating the range tracker with hardware in the loop measurements, a generic study of chaff effectiveness and areas for further development complete the report.

2.0 ASSESSMENT APPROACH

The assessment scope chosen here is strongly influenced by the guidance provided in Simulation Validation published by IEEE [3]. In this publication it is pointed out that simulations must be sufficiently accurate for the purpose for which they are to be used. Generally speaking, their accuracy can be tested for a given scenario by a comparison with analytic results, by comparison with other models and with measured data. Usually as the complexity of the simulation increases, the analytic approach can only be used on the components. This is most economically done and is usually done by the developer as the code is written. Comparison of a simulation with other reference models may also be employed to check simulation accuracy, where such reference models are known to be accurate and where they simulate the same scenarios. Such tests can be used to affordably test or compare a simulation over a range of conditions. The entire simulation model can also be benchmarked against data from trials, should such data be available. This would provide a test of a model's validity but would not allow extensive validation of a simulation code for all scenarios appropriate to the code.

The assessment described here summarises the assessments performed and documented by the software developer in the validation of the individual components. It also summarises any documentary information on the conceptual model, on the security of the software and most significantly describes the results from beta testing. These results include recommended software modification and development. The intention is to bring together, in a concise way, all the existing validation information and to add to it the results of validating the CJASCM.

A limited assessment [3] was chosen because of limited resources and because a three-dimensional version of CJASCM is under development. The three-dimensional code will model linear motion of the missile and chaff in three-dimensions and the pitch or yaw but not the roll of the missile. Limited assessments are performed to ensure that the code is modified through corrections and enhancements in the next development phase if and when modifications are considered appropriate. It is recognised that trial data measuring missile performance for all of the Electronic Warfare (EW) parameters is not likely to be available, and certainly analysis of such data would not be within the scope of this study. Since a limited assessment would normally compare data from such trials to simulations, the assessment described here is a partial limited assessment.

At the completion of a three-dimensional version of CJASCM, another maintenance assessment would be required. The least that could be done is a comparison between the output of the two and three dimensional versions, for the cases previously run, with documentation of the enhancements in the three dimensional version. If a complete trial or experimental data set can be obtained, that can be simulated by CJASCM, an experimental validation could be attempted. Should resources be available, and the need arise, there are two higher levels of assessment that can be used to provide increased levels of confidence in the code. These levels, known as limited and formal assessments, are both more extensive in the testing performed and

in the aspects investigated. Although desirable, such assessments are presently beyond the resources available for the purpose in the Electronic Countermeasures Section at DREO.

In a limited assessment the purpose is fourfold although limited in scope and detail. First, the intention is to determine the degree of credibility based on the development efforts. Second, it is to characterise the model to identify capabilities for potential users of the model. Third, it is to identify risk areas or limitations of the applicability of the model based on the model's stated application and, finally, to provide an analytic basis for further assessment. For CJASCM the latter would probably refer to assessment of the three dimensional version of CJASCM.

2.1 Conceptual Model Validation Approach

In this assessment conceptual validation consists of developing a written description from that found in documents referenced herein and other available Electronic Warfare (EW) references. If more information on the conceptual model is required than is available in the users guide and milestone reports, an examination of the code is employed to determine what the software model appears to be. It should be noted that such an approach is only used where information is otherwise lacking and is therefore inherently higher risk. This reverse engineering, when necessary, usually provides the developer with feedback regarding the model and documentation. As a result the conceptual model or documentation may require modification. Conceptual Model Validation is a necessary step because it describes and comments on the conceptual model that is assessed in the software verification and operational validation testing.

The reverse engineering by examination of the software is made more difficult by the fact that the parameters conveyed by a link between modules are not unambiguously identifiable. This difficulty is being addressed in the 3-D version by placing dummy modules on a link that identify the parameters and their order. These dummy modules are identifiable by both their colour and their shape.

2.2 Software Verification Approach

Usually the developer provides documentary evidence that the code simulates the intended model. Further software verification was achieved by visual examination of the modules and expressions in the code to determine whether the code reflected the conceptual model. The conceptual model is considered to be that described in section 3 and documented in the users guides and milestone reports. Only more noticeable discrepancies could be investigated with the resources available. The process aids the assessor by providing feedback on what was coded. This fills gaps in the conceptual model. When a code runs in a manner not initially intended, as is often the case during development, the software may be altered after a module is written. Sometimes this leads to a change of the conceptual model from that documented. When and if what appear to be discrepancies are found they are reported so that changes to the software, conceptual model or assessment document can be made.

In all fairness to a software developer, a significant component of the risk in developing code based on a fifth generation language may be attributed to risks associated with the development language. Such risk negates some of the benefits of using a fifth generation language since components of the fifth generation language's library may not be valid. Using a developer's routines may represent a higher or lower risk.

2.3 Operational Validation Test Approach

Operational validation would ideally consist of comparing the outcome of a field trial for a missile engagement with the CJASCM simulation prediction. Unfortunately, many parameters that are required to fully specify the trial scenario are not available for existing accessible trial data. In the real world, trial data for such a complex scenario usually falls short of what is required for operational validation. There is however a continuing effort to increase the number of parameters recorded in such data sets. It is this uncertainty of the parameters and of the measured outcome of an engagement that make validation from trial data not only an expensive but also a very imprecise and therefore unsatisfactory process. Since such data is also likely to be classified, analysis would demand additional resources, and such analysis if carried out would be the subject of a separate document with limited distribution.

Ideally under laboratory conditions it is also possible to isolate a jamming or deception feature and compare it with simulation results by adjusting the scenario to one that can be modelled both in the laboratory and with CJASCM. This enables an end-to-end comparison between simulation and laboratory data for what may turn out to be a rather specialised scenario. In a joint effort with the developer, data obtained under laboratory conditions was employed to benchmark some parameters employed in CJASCM. Laboratory measurements have the advantage of allowing better control over the data collection. This approach was applied to the MG-13 radar for which the values of some intermediate electronic parameters are presently beyond our resources to monitor in this study.

Since laboratory data is limited to available equipment and whatever can be measured in a laboratory, only certain simulation components can be evaluated in this way. Consequently data calculated from analytic expressions or with models was employed to assess some components.

Operational validation may also be employed to determine over what range of parameters the simulation provides accurate solutions. Examining the underlying analytic expressions for the simulation would be employed to identify parameter values for which the code is likely to be less accurate. By carrying out runs for a range of parameter values, including those where code output could be less accurate, anomalous behaviour or imprecise results may be identified. Where resources permit, further investigation of the underlying cause would be advisable. Accuracy may be reduced by failure of the underlying development language, of the approximations in the model, through coding difficulties, conceptual limitations or hardware failure. Extensive investigations of this nature are beyond the scope of this report. However

some components, which had been shown by the developer to not be as intended in the conceptual model, were investigated.

An investigation of the performance for a countermeasure, as a function of the parameter values of the countermeasure, would provide further validation of the model and insight into the effectiveness of EW techniques. Such an investigation represents a beta test available as an option to DREO under the DIR contract.

3.0 SIMULATION DESCRIPTION AND EVALUATION

In the following description the model properties found in the CJASCM users guide [4], as well as the content in the milestone reports [2], [5], [7], are brought together and summarised. Thus, section 3 serves to describe the model features deduced from the V1.2 software and the milestone reports. CJASCM is a member of a suite of one-on-one engagement models of a single missile targeted on a single platform. Each TESS simulator models a class of missile for a particular scenario [4]. Simulators are defined by, (a) engagement type; surface-to-air or surface-to-surface, (b) guidance type; active, semi-active, passive homing or command guidance, and (c) seeker type; monopulse, lobe-on-receive-only or scan with compensation. CJASCM models engagements between a sea-skimming missile, which uses active radar homing and monopulse processing, and a ship which has the capability of active on-board deception jamming and chaff deployment. Version 1.2 of CJASCM is a two-dimensional model of the terminal phase of the engagement in that the missile position has only x and y co-ordinates in the horizontal plane and a constant missile altitude. This is a three degree of freedom model since missile heading is also a model variable. Evaluation of the three-dimensional model, which is under development to extend the two dimensional model to include motion in the vertical, is outside the scope of this report.

Simulation of the terminal phase of the ASM engagement is on a time-slice basis with the radar pulses of specified width but with no detailed representation of the pulse shape. Detection is based on the received level in the range gate exceeding a threshold which is set 13 dB above the clutter level at all times. This is not a pulse by pulse simulation. The simulation introduces a risk in that it may not represent the statistics of the signal-to-noise ratio faithfully. Investigation of the tracking algorithms would be required to verify whether the integration gain of the tracker is modelled correctly. It is not anticipated, at this time, that this issue will be addressed differently in the three-dimensional version presently under development.

The accuracy of results obtained when using a time-slice approach also depends on the time interval between samples. To determine whether the time interval is small enough one may repeatedly halve the time interval until the missile trajectory converges to a stable result. This approach is often used when a numerical analysis is performed but is only as accurate as the numerical representation. Difficulties can be encountered where evaluations closely spaced in time do not represent the physics of the problem. No instances of this have been identified.

The model is written in the fifth generation development language Simulink that is built on Matlab. This has the advantage of reduced coding time and of producing a compact graphical presentation of the schematic representing the software and of using built-in models for which the step size is automatically set to achieve specified accuracy. The graphical representation acts as documentation. In the process of validating the code it is found that determining the nature of the software behind the modules requires a very thorough examination of lower levels in the model. Since such an investigation for all the modules is beyond the scope of this validation, all the levels were examined only for suspect modules.

The particular implementation of CJASCM in Simulink and Matlab is a modelling process where the physics of each aspect treated is analysed and implemented in a separate module at a level appropriate to the approximation. This therefore results in a code that requires extensive modification if it is to be extended and partially defeats the maintenance advantages of a modular code written in a third generation language such as FORTRAN or C. Furthermore, each module is repeated and must be edited then pasted into each instance if changes are to be made to the code. This could be avoided by the use of Simulink functions, models converted to C or models in Matlab, but this would negate the openness of the software.

3.1 Input and Output

Users interface with the software through a Simulink schematic in which parameters for the simulation are input manually through a set of dialog boxes accessible from the schematic. Computational assistance is available for setting parameters such as the RGS velocity and acceleration and a default set of parameter values is provided in the dialog boxes and in the modules. The user enters parameter values into the dialogue boxes for each module on the first level schematic of Simulink. Other parameters are accessible in the modules. Such a method associates the parameters with the modules but is in danger of resulting in poor tracking of simulation runs. A front end is being developed in Microsoft Access for the three-dimensional model to address this issue.

The model output includes the x-y trajectory of the missile, the path followed by the targeted platform and the motion of the chaff cloud. The missile's tracking and flight path errors are also plotted, as a function of time, as oscilloscope displays called scope displays. In one scope display the difference between missile heading and the direction from the missile to the ship is plotted. In a second display the ranges from the missile to the chaff cloud, Range Gate Steal (RGS) pulse and seeker tracking-gate are plotted In a third scope display the angle between the missile seeker's boresight direction and the direction from the missile to the chaff cloud are displayed. In all, there are six oscilloscope displays in addition to the x-y display. Some of the calculated parameters, such as miss-distance, are available at the termination of a simulation in the Matlab workspace. The simulation terminates when the distance between the missile and the platform increases, the assumption being that the closest point of approach has been reached. The simulation also terminates when the maximum execution time is exceeded. The run time output to the x-y plot and scopes slows the simulation by at least a factor of two. This can be avoided by transferring the x-y plot information to the workspace and using a Matlab M-file and

a Simulink library module to execute the M-file after the simulation is complete. Scope modules can be opened at the completion of the simulation.

3.2 Propagation Model

The environment is modelled with a multipath propagation model to represent the constructive and destructive interference between direct and surface bounce paths for the jammer. Spreading losses and time of arrival are assumed to be the same for direct and reflected paths but the path length difference for the short ranges to be modelled is based on a flat earth model and a low altitude missile. The phase shift on reflection is modelled as 180° and the reflection coefficient is modelled as that due to the sea surface roughness with the Fresnel coefficient set to unity. Multipath, glint, reflection coefficient fluctuations and polarisation fluctuations are not modelled for the ship and chaff.

The user specified wind speed is used to determine the rate at which chaff drifts and the sea state number is set separately. The simulation treats the Beaufort wind-scale number as being about one less than the sea state number. The multipath model consists of a linear approximation to the direct path and a surface bounce path with the level of interference a function of sea-state. The user specifies the sea state number, independent of the wind speed, from which the RMS deviation of the sea surface is determined and thence the specular reflection coefficient. Because the altitude of the missile and the jammer are similar, it is necessary that an exact expression be used for straight-line propagation rather than an approximation. The reference plane for jammer and seeker azimuth is horizontal and the polarisation is horizontal. In order to model the effect of the antenna pattern, away from the horizontal, on the received power at the missile seeker, the specular coefficient is multiplied by the sinc^2 function antenna pattern.

The developer demonstrated that the interference from sea surface reflections varied from a maximum at sea state zero to no interference at sea state 9 as described for the conceptual model.

3.3 Radar Reflection Models

Clutter from sea surface reflections is modelled as having a Rayleigh distributed amplitude in time with mean and variance of the clutter level dependent on the sea-state. The correlation of the fluctuations is not accessible in a dialog box; however, the seed for selecting the fluctuations may be a constant or a time dependant variable. In addition to the effect of sea-state, seeker transmitter lobe width and missile cruise altitude are modelled. By the central limit theorem the Rayleigh distribution is a first approximation to the clutter distribution since the distribution results from the real and imaginary components of the radar output and each component is likely to approach a Gaussian distribution. If details of the true distribution shape and correlation are required, then the approximation of a Rayleigh distribution will require modification. The Rayleigh distributed amplitude of the clutter model may also be described as an exponential distribution in power.

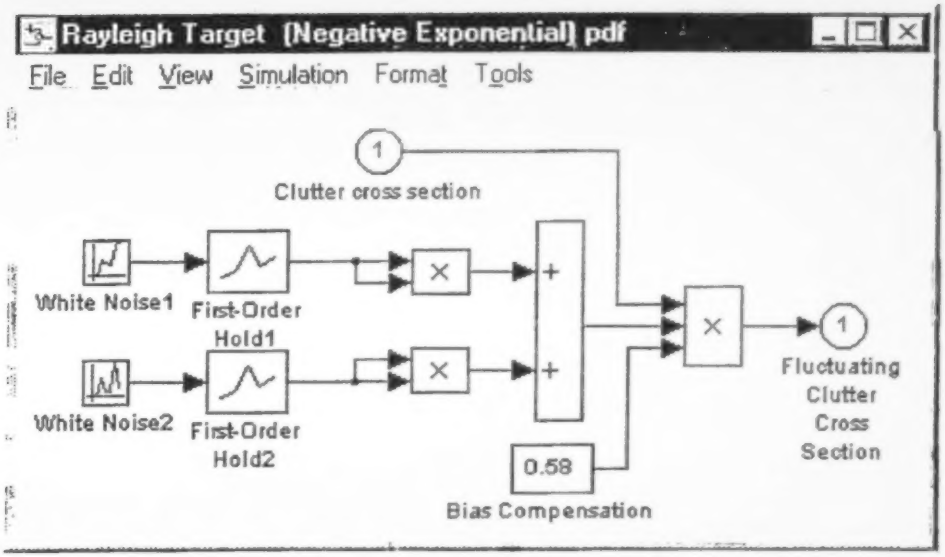

Figure 1. Clutter Rayleigh Target Block in CJASCM Version 1.2.

Numerous details of the clutter are not modelled. Polarisation of the outgoing and return signals is not modelled. The effect of wind direction on the average clutter level and the effect of wind speed on the clutter scintillation, are not modelled. The model treats the clutter as the same for all range gate cells and treats the earth as flat. No account of the effect of clutter entering through sidelobes is made, the clutter is assumed to lie well within the horizon and surface reflectivity is represented by a constant gamma model.

An exponential distribution is generated to model the clutter, ship and chaff RCS in the Rayleigh block illustrated in Figure 1. The developer found that the average clutter cross section was not the same value as the mean of the exponential target distribution. This was attributed to the non-independence of the Gaussian pseudo-random distribution [2] pp. 26. The average clutter cross section was made to equal the mean of the exponential distribution by applying a bias of 0.58, 0.55 or 0.8 for the three applications of the Rayleigh block. These bias values should be the same for all of the instances. The,

$$mean\ exponential = 2(standard\ deviation\ Gauss)^2$$

and the exponential distribution is derived from a (0,1) Gaussian distribution. Thus the mean of the exponential would be 2 and a bias of 0.5 would be required to ensure that the mean RCS is as intended. In a Simulink simulation it was confirmed numerically that a bias of 0.5 is required when a Rayleigh distribution is formed directly from two pseudorandom Gaussian sequences with no correlation. Thus the discrepancy is the result of the sample and hold in the Clutter Rayleigh Target Block shown in Figure 1 that was introduced to prevent division by zero during execution.

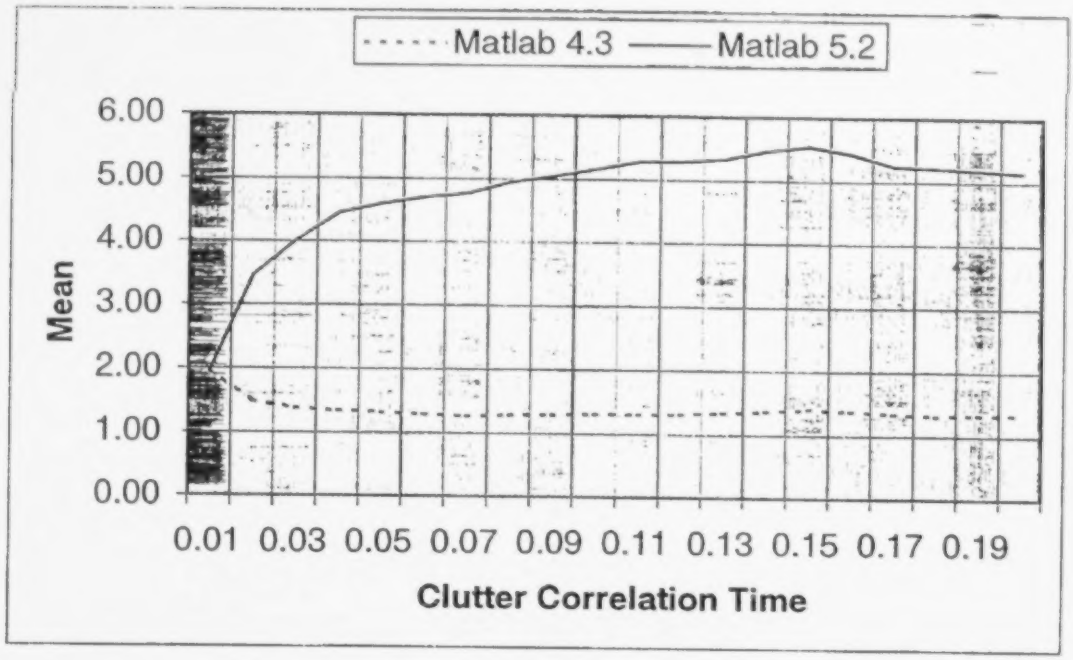

Figure 2. Mean of Rayleigh Distributions for Matlab 4.3 and 5.2

Mean of the Rayleigh distribution for a bias of 1.0 and an RCS of 1.0. Lower curve from the Rayleigh clutter block using first order hold from Simulink Version 1.3c with Matlab Version 4.3 and upper curve using the first order hold from Simulink Version 2.2 with Matlab Version 5.2.

The sample and hold alters the variance of the underlying Gaussian distribution and a partial correction equal to the reciprocal of the number of interpolates is introduced in the Simulink first order hold module. It was confirmed that variation of the correlation of the hold produces a variation of the mean of the exponential distribution. Thus a bias that varies with the ratio of the sample time to the correlation time is required, whereas a fixed bias was employed in Version 1.2 of CJASCM. The mean RCS calculated with the 'Rayleigh' blocks is illustrated in Figure 2 for Simulink Version 1.3c with Matlab Version 4.3. If the new sample and hold of Simulink Version 2.2 Matlab Version 5.2 is used in place of the sample and hold of Versions 1.3c and 4.3 there is an even larger discrepancy between the intended and modelled RCS as illustrated in Figure 2. One solution is to use a lookup table to determine the appropriate bias for the values of sample time and correlation time in use. The developer resolved this in the next version by developing a model in Cjascm23 that does not include sample and hold. The RCS is now as intended but small correlation times may result in errors and therefor can not be used reliably.

In the seeker angle-range-tracker block the clutter power density is converted to a voltage with arbitrary zero phase in both the left and right antenna lobes. It is reasonable to expect on average a zero phase clutter but this is not likely to be the case at any particular instance. This could have been modelled as a distributed phase and would have a bearing on the cumulative clutter level for multiple samples. Since clutter is modelled as zero phase for both lobes, differences incorporating clutter would either add constructively or destructively. This would result in a level that is at times higher or lower than would be encountered in practice. The use of zero phase is a placeholder that can be replaced by a more realistic model.

The RCS for ship and chaff are modelled as frequency independent, independent of pulse width, with no glint, phase fluctuations or polarisation fluctuations. RCS distributions are derived from a pseudo-random Rayleigh distribution to represent chaff in its saturation state. The statistical properties described for all of the three reflection models may also be applied stochastically.

The ship is modelled as a moving point target with an aspect dependent RCS. The RCS scintillates about the chosen mean value according to a Swerling 1 model. This corresponds to a Rayleigh distributed amplitude, as for clutter, but with an RCS appropriate for the particular ship aspect. The ship's motion may be specified as linear or to include a single turn. However, the software will not allow a turn exceeding 360 degrees. This is not considered a very serious practical limitation. Although the lateral acceleration of the ship is limited to 10g the software is easily edited to alter this limit for test purposes.

3.4 Electronic Countermeasures Models

Electronic Countermeasures (ECM) include both active and passive. The active jammer on the ship includes Range Gate Steal (RGS), blinking and cross-eye ECM techniques. Any one of RGS, blinking and cross-eye may be simulated. Alternatively either blinking or cross-eye jamming may be employed in conjunction with RGS. Turning off RGS or both of cross-eye and blinking can be achieved by adjusting RGS levels or ECM parameters. The jammer model has two synchronised transmitters, each with its own antenna, with a user specified antenna separation up to the length of the ship. The magnitude and phase relationship of the transmitters is a function of the ECM technique that is being simulated. Tracking of the missile by the jammer is not modelled, rather the jammer is assumed to track the missile perfectly and to always point at the missile.

Ship position and antenna position are shown on an X-Y plot. The antennas are on a line joining bow and stern of the ship with the ship modelled by an RCS at a point mid way between the antennas. If the display resolution is sufficiently high to resolve the centre, bow and stern of the ship on a curved track these three points will be visible in the X-Y plot. For Cross-Eye jamming the signal received from the seeker on antenna one is retransmitted from antenna two while the signal received on antenna two is phase shifted and retransmitted from antenna one. The phase shift may be the classical 180° or a symmetrical sweep about a user specified centre and a user-specified phase width and rate. Blinking jamming includes the ability to select a band

of blinking rates and the rate of sweep over this band. An additional phase delay is introduced to both jammers. This delay represents time for the signal to propagate within the ship between the two antennas as well as the delay introduced by the countermeasures processor. A delay for implementing Cross-Eye is also specified by the user. The effect of Cross-Eye in producing an angular error was demonstrated on pp. 60 of Milestone 1. However the jammer phase is shown to be plus or minus 15 degrees when the phase sweep excursions are stated to be plus or minus 90 degrees. For the blinking jamming mode the power levels were confirmed to be equal to the product of the antenna gain and the jamming antenna transmit power. The rate of blinking and the alternate transmission from first one then the other antenna was also confirmed. The ship's antenna positions may be observed from the X-Y plot during simulated manoeuvres and was confirmed to be correct during this validation.

Version 1.2 of CJASCM models a single passive chaff cloud of specifiable aspect angle dependent Radar Cross Section (RCS) with launch parameters and cloud dynamics. Cloud dynamics depend on the wind parameters. Like the ship, chaff is modelled as a moving target located at a point with a scintillating aspect-dependent RCS but modified by launch, grow and decay parameters as well as scintillation correlation time, launch velocity, wind speed and direction.

3.5 Missile Model

The missile model consists of a *transmitter*, a *seeker*, an *autopilot* and an *airframe*. There is an option in the TESS suite outside of CJASCM to replace the active or semi-active homing, modelled by the seeker, with command guidance, modelled by a fire control system.

The *transmitter* block dynamically calculates line-of-sight directions to the platform and the electronic countermeasure objects, and then generates simulated signals along these bearings. To avoid range ambiguity, the range gate position is limited to 0.1 milliseconds, or 15 km, from the missile as would be expected for Pulse Repetition Frequencies typical for a transmitter in this application. This parameter may require adjustment to model a high PRF seeker transmitter.

The *airframe* model calculates the missiles aerodynamic response to autopilot commands. Missile body dimensions, maximum lateral acceleration and velocity determine the missiles aerodynamic characteristics. The aerodynamic characteristics are at best a first approximation and do not account for the aerofoil thickness, cross-sectional shape and planform shape. Thus to accurately model a specific missile it might be necessary to modify the airframe model to take any critical feature into account such as wing sweep, taper, number of wings and their location. On the other hand such features may be modelled for a particular missile, if such an approximation provides sufficient fidelity, by changing the aerodynamic coefficients for the missile in the present model.

3.6 Seeker Model

The *seeker* models the antenna pattern, AGC, angle tracking servo and range tracker. In a different model from CJASCM in the TESS suite, Doppler tracking is modelled. The missile angle tracker and the range tracker realistically model such trackers. The former compares the energy in the left and right lobes while the range tracker compares the energy in the early and late gates. This information drives the respective tracking servos. In Version 1.2 the seeker model incorporates a selectable chaff rejection capability. This capability is based on measuring the energy in the left and right antenna lobes at the output of a high pass filter. Chaff can be recognised by its short correlation time that results from its higher scintillation frequency. A large output from the filter is considered representative of energy at higher scintillation frequencies. The gain in the channel with the highest level of high frequency energy is reduced to favour targets with a low energy at high scintillation frequencies. The cut-off frequency for the filter is typically set at a few Hz. This is considered sufficiently low for the scintillation frequencies exhibited by chaff under low turbulence conditions.

The same chaff rejection capability is implemented in the range tracking circuit. For the range circuit the energy at high scintillation frequencies in the early and late gate signals are compared.

3.7 Modern Autopilot Algorithm

The *autopilot* model converts the tracking information into steering commands for the airframe based on a proportional navigation model. In CJASCM the autopilot algorithm employs an optimal proportional navigation coefficient where the missile trajectory's angular rate of change is proportional to the rate of change of the missile's line of sight to the target. It is assumed that the missile performs no roll movement, travels at constant speed, there are no wind effects, the missile's mass is constant and the target velocity is known to the missile at all times. Certain other assumptions are also made namely, that the ship is considered to be a point target, glint, i.e. apparent position of the reflector, is not modelled and the target or ship speed is considered to be constant. In the implementation, the ship velocity, ship heading, missile velocity, missile heading and flight path angle are supplied to the autopilot block. The field of view is limited to a maximum angle corresponding to the gimbal limit of the antenna. The user also sets the maximum value of the navigation coefficient. At the initiation of the simulation run the simulation assumes that the missile is able to deduce the required track position information from its radar, i.e. that tracking is perfect. Since this will only be the best case scenario, from the missile's point of view, missile performance will tend to be overestimated at this time. To obtain a more realistic estimate the software would have to incorporate the simulation of the estimation of these parameters. Loss of track is simulated as discussed in sections 3.8 to 3.10 so that despite the assumption of perfect tracking for the seeker at the commencement of the simulation, the seeker can still loose lock and go through the search and acquisition phase.

A test analysis documented in the second milestone report confirmed that the calculated navigation coefficients agreed with the values expected for the equations implemented in the

code. In CJASCM 1.2 the actual ship velocity and heading are used to adjust the proportional navigation coefficient. In the 3-d version under development estimates of the target position and velocity will be employed to adjust the proportional navigation coefficient.

3.8 Seeker Mode Switching

The seeker mode switching module simulates the switching of the radar search pattern and tracking from a broad search to acquisition and then to tracking. On loss of track the search and reacquisition process restarts. During the search phase the detection of a target is simulated while during the acquisition phase the detected target is tracked until a threshold level is exceeded over a longer time interval. In the search phase the radar scans back and forth in azimuth while performing two range searches for each 3 dB beamwidth movement in azimuth. This scanning is like a raster scan for a TV with range across the TV screen and azimuth down the screen and no interlacing. The antenna properties and range search rate specified in the software model are used to determine the range gate search width, i.e. the displacement in azimuth between successive searches in range. To minimise overlap in the search phase, the simulation optimises the value of range search width for the given angle search width, range search rate and angle search rate. In the tracking phase the width of the range gate is reduced enabling a higher resolution of the target range. Simultaneously, the seeker is also switched to servo control. The smaller range gate would enhance the signal-to-noise ratio. This SNR enhancement is not modelled in the software and is not likely to alter performance at the terminal phase of an engagement. The azimuth servo bandwidth also narrows after a pre-set delay. If the seeker is successful in locking on to a track then it switches to the tracking phase.

Detection is based on exceeding a threshold while target track lock or break lock is based respectively on exceeding or falling short of M out of N detections. During the search phase the N detections are likely to be made over a shorter period than in the acquisition and tracking phases so that N is therefore likely to be smaller. This shorter period is defined by the range search rate, reacquisition gate width and simulation step size [5]. To make the code efficient, the modules required for a given tracking mode are only enabled when that mode is required. Mode switching, angle search and range search were tested by the developer and demonstrated to operate as described. These checks were quantitative in nature and employed RGPO to break lock so that mode switching was triggered.

3.9 Range Search

A non-tracking range search gate, three times the tracking gate width with a lower limit of 5μs, is employed to detect the presence of a target. The range compensation module is used to maintain the centre of the range sweep at the position where target track was lost. It subtracts the integrated missile velocity from the current range position for the next sweep. The sweep generator azimuth is set to zero at the start of a new reacquisition phase. The sweep-delay module delays the range sweep by one detection-time period after the start of the search mode. The direction of the initial range search, and the direction of subsequent searches, are set by the user.

3.10 Angle Search

The user sets the width of the angle search, limited to a maximum of twice the gimbal limit. For the first 0.3 seconds of the acquisition mode the azimuth servo bandwidth is increased by a factor of six times that specified by the user to produce a stable response. This is done to centre the target in the antenna beam after it has been detected so that the autopilot can be turned on as soon as possible. The autopilot activation is delayed by 0.4 seconds, 0.1 seconds longer than the 0.3 seconds delay for increasing the azimuth servo bandwidth. Acquire track threshold is set at 0.5 volts and the lose-track threshold being set at 0.2 volts with maximum level being 1.0 volt.

Mode selection is based on the RMS level in the range track and search gates. This RMS level is the total RMS value of the ship, chaff, jamming and clutter although the clutter is not mentioned in the documentation. The use of the RMS level may not accurately represent the process in a missile. It is an approximation that accounts for the phase variations among the pulses in an average sense.

An M out of N tracker that is reset every N time steps was chosen for ease of implementation. The M out of N tracker is reset every N time steps or when there are less than M detections in N. Thus the windows form a contiguous fixed set in time, each window of N time steps, this is not a model of a moving window. The target track is held if there are at least M detections and is lost if there are less than M detections in the window of N time steps. N is set equal to the user input Memory Time (MT) divided by the step size. Reporting of loss of track occurs at the instant that the number of non-detections reaches N-M in a block of N or there are detections in less than 50% of a window exceeding the memory time. While this model is appropriate for some missiles others may use a moving window rather than resetting the tracker every N steps.

For acquisition, the same process is used but MT is replaced by the Range Gate Width divided by twice the Range Search Rate.

The adaptive thresholding models the clutter measurement as the sum of clutter and any returns from the ship, chaff and signals from the jamming antenna. The clutter gates position is placed at a constant offset of 1μs or 150 m in range from the range gate and the clutter gate width is four times the user specified track gate width. The clutter gate offset is either towards the missile or away from the missile as specified by the user. Thus the gate centres are separated by 1μs plus half the sum of the range gate width plus clutter gate width. For tracking the range gate width is the track gate width, specified by the user, while for search and acquisition it is the wide gate width. The latter non-tracking range gate has a width of three times the tracking gate with a lower limit of 5 μs. The signal in the clutter gate is low pass filtered and vectorially added to the range gate maximum level. In Version 1.2 of the software only one clutter gate is used. During simulations the gate may fall over the ship or chaff resulting in an anomalously high clutter value so that the level in the range gate over the missile falls below threshold and the seeker goes into search mode. The likelihood of this happening can be reduced by using the level of the lowest of

two clutter gates if this is representative of the missile being modelled. Although a single clutter gate does result in anomalous performance this is just what would be encountered if the clutter gate were implemented in this way in the missile.

3.11 Subsonic and Supersonic Flight Modelling

The modelling of the missile's airframe aerodynamic parameters takes into account the compressibility of the air, which affects lift, drag and turning moment coefficient at speeds exceeding Mach 0.3. Transition between the subsonic and supersonic regions is achieved by numeric curve fitting. The moment of inertia of the missile is modelled as that of a uniform cylinder and does not consider the change in the missile's mass as the fuel is burned i.e. the mass of the missile is assumed to be constant. Running the simulation with different masses shows that this changes the missile miss distance by a significant amount and represents an aspect in which the model would benefit from refinement. The aerodynamic model of the wings treats the aero-foil wings as thin and the lift and turning moment as independent of detailed wing planform shape.

Below Mach 0.3 Newton's equation for rectilinear motion and Euler's equation for rotational motion are employed. Motion of the missile is restricted to two dimensions and roll is not permitted. Thus only altitude and roll stabilised missiles are modelled. For rectilinear motion, lift on the control surfaces is neglected and the relationship between the lateral acceleration and the control surface deflection takes the standard form for a second order control system with two parameters. These are the airframe's damping coefficient and its natural resonance frequency.

The equations defining the forces applied to the airframe below Mach 0.3 are determined from the Navier-Stokes equations where the approximation of a small angle of attack is assumed. At larger angles of attack, turbulence would also have to be taken into account; a condition under which aerodynamic stall would occur. This is not likely to be the situation for a correctly designed missile and therefore is not a significant limitation of the model. The moment coefficients for large aspect wings and small aspect wings are blended in a numerical model to cover aspect ratios from 0 to 10. In the numerical model the moment coefficients are also reduced at high aspect ratios to model the moment coefficient measured in practice.

At missile speeds between Mach 0.3 and 0.7, the lift coefficients are increased by, $1/\sqrt{1-M^2}$, where M is the Mach number. These are the only modifications to account for the effect of changing missile speed for this speed regime.

4.0 OPERATIONAL VALIDATION TESTS

In this section two forms of validation are described and discussed; first, validation of particular model components in CJASCM, based on laboratory data, second, beta testing as required in the DIR contract. In the beta testing multiple simulations were carried out. These illustrate the practicality of carrying out performance assessment for situations of interest and,

where unexpected results arise, may uncover any shortcomings in the code. The performance assessment also gives some insight regarding the nature of the chaff effectiveness function in a first step towards estimating chaff effectiveness. When the 3-D version of CJASCM is available from the developer a validation of CJASCM against the previously validated software would be appropriate.

4.1 Laboratory Validation Tests

The DREO simulation facility provided the opportunity to measure the response of an MG13 radar to target range steps and to Range Gate Pull Off (RGPO) for the purpose of validating the model of range tracking in CJASCM. The MG13 radar was used in the Voodoo Aircraft about three decades ago and still provides a physical realisation of the radar and tracker of some anti-ship missiles. Because of the fragile nature of the radar and the time consuming nature of the measurement process, a restricted set of scenarios compatible with both the CJASCM software and the laboratory facilities was identified. In order to make the measurements software was written and an electronic interface between the Electronic Warfare Engagement Simulation Facility and a PC was completed. This was done in order to enable radar signals to be generated that represented the reflection of the MG 13 pulse corresponding to one or two programmable target ranges at any one time. A data collection system was also implemented on the PC.

The first set of measurements was to determine the response to 40, 60, 80, and 100-m jumps in target range. This was intended to determine for what step size the MG 13 was unable to maintain track and to determine the step response. The latter enables one to estimate the damping and resonant frequency of the range tracker. These measurements resulted in an estimate of 0.37 for the damping coefficient and 2.2 radians/sec for the resonant frequency assuming a Type I model for the tracker. By setting the split-range gate very wide and making the transmitted pulse half as wide it was possible to mimic the MG13 tracking discriminator curve with CJASCM. CJASCM, which has a Type II servo, was then used to simulate the response using a 3 dB bandwidth of 0.49 Hz the same bandwidth as for the Type I model. The MG 13 tracker was able to maintain track for range steps of up to 60 m. The simulation followed the step more closely than the measurements as would be expected for a Type II servo. These results support the validity of the CJASCM range tracking simulation component. The scope of the study did not permit the substitution of a Type I servo model in CJASCM to more accurately model the MG 13 tracker.

The second set of measurements was to determine the response of the MG 13 to Range Gate Pull Off (RGPO). It was found that the MG 13 followed the RGPO for RGPO rates up to 100 m/s for an RGPO-to-ship RCS ratio of 0 dB and 120 m/s for a 6 dB ratio. When the parameters determined from the range step measurements were employed in CJASCM to simulate RGPO the maximum RGPO rate for which the simulation maintained track was 100 m/s at 0 dB. The simulated response to RGPO was also closer to the range step input than the measured response. This is as would be expected for a Type II as against a Type I servo. Thus the RGPO results also validate the CJASCM range tracking simulation.

4.2 Chaff Effectiveness Simulations

This section describes a preliminary generic study aimed at exploring the utility of the CJASCM software. The generic study determines the effectiveness of chaff for defending a ship in the terminal phase of a missile engagement. The effectiveness of chaff was measured by the missile's miss-distance, which is a function of the simulation parameters. Knowledge of this function's properties is fundamental to identifying an EW tactic for chaff.

To reduce the complexity of the problem in this study, we chose an investigation of chaff effectiveness, without RGPO. The RCS of ship and chaff were also made isotropic and the same seed was used for each simulation to minimise variations from run to run. By using the same seed for each simulation statistical variations from run to run that would introduce asymmetries are eliminated. Thus any software errors would, for example, be more noticeable as unexplained spatial asymmetry. First, with a fixed scenario, we investigated the effectiveness of chaff placed at ranges up to 1.2 km and bearings between 0 and 360 degrees, both relative to the ship. Chaff was always launched to positions on a 200-m grid along x and y co-ordinates. Next we investigated the effect of wind speed and missile direction, relative to the ship, on the chaff effectiveness function.

The default parameters supplied with CJASCM are listed in Table I and were used, except as described below, in this study. The heading and the positional parameters of ship, chaff and missile were varied and are identified by an asterisk. The missile parameters are in the range of those required for an effective missile design as discussed in the TESS documentation referenced.

The geometry was chosen to be representative of the terminal phase of the engagement of a missile on a ship. The missile was directed at the ship from a range of 9.9 km in an acquisition mode. This lies between seduction and distraction because the missile is acquiring a track and knows precisely where the target is. It would be seduction if the missile were locked on to the ship. Since the chaff is near the ship and the seeker is usually close to lock on in these simulations it approximates seduction. This ambiguity is avoided in the next version of the software by starting the missile in tracking mode. For investigations of interest to DREO it would be better to have the mode user selectable at the commencement of the simulation. The chaff RCS was set 3 dB above the ship RCS to ensure that the chaff was effective for a significant number of locations. Clutter was low, sea state 3, so that it did not influence the miss distance. This choice of parameters would ensure that miss distances were a function of a few parameters and therefore that they could be readily interpreted. To seduce the missile Chaff was launched one second after the missile reached a range of 10,000 m from the ship, which implies that the true launch time was as much as 16 seconds earlier. The timing of chaff launch requires a more realistic model if batch runs of large sets of realistic simulations are to be carried out in a timely manner.

Table I Default Simulation Parameters

Seeker Transmitter	Antenna Diameter (m)	0.3
	Radiation Efficiency (%)	60
	Transmit Frequency (GHz)	9
	Power (kW), PRI (ms)	40, 1
	Pulse Width (microseconds)	0.25
Ship	Ship Initial X Position (m)	7000
	Ship Initial Y Position (m)	7000
	Ship Speed (m/s)	7.5
	Initial Heading (Deg CW wrt North)	-45
	RCS Aspect Angle (-180 to 180 deg)	-180, -100, -90, -80, 0, 80, 90, 100, 180
	RCS Value (dBm^2)	30, 30, 30, 30, 30, 30, 30, 30, 30
	Lat Acc (g)	0
	Final Heading (Deg CW wrt North)	-45
	Time of Turn (s)	10
	RCS Correlation Time (s)	0.5
	Vulnerability Area (m^2)	1000
	Stochastic Ship RCS Scintillation	Off
Chaff	RCS Aspect Angle (-180 to 180 Deg)	0, 180
	RCS Value (dBm^2)	33, 33
	Bloom (Tau (s))	0.1
	Bloom (Delay (s))	1
	Decay (Tau (s))	30
	Decay (Delay (s))	45
	Chaff Launch: Direction (Deg wrt Ship)*	135
	Chaff Launch: Distance (m)*	700
	Chaff RCS Correlation Time (s)	0.05
	Stochastic RCS Correlation Time (s)	Off
Receiving Environment	Sea State, Wind Speed (m/s)	3, 5
	Wind Direction (Deg CW wrt North)*	135
	Stochastic Clutter Scintillation	Off
Seeker Receiver Processor	Servo Bandwidths: Range (Hz)	0.57
	Servo Bandwidths: Azimuth (Hz)	0.6
	Servo Bandwidths: AGC (Hz)	8
	Range Track Gate: Width (microseconds)	0.5
	Range Track Gate: Bias (dB)	0
	Initial Range Search Direction	Out
	Angle Search: Width (deg)	20
	Angle Search: Rate (deg/s)	8
	Initial Angle Search Direction	Left
	Gimbal Limit (deg)	20
	Track Mode: Memory Time (s)	0.3
	Enable Chaff Rejection	Off
	DSP: HP Cutoff (Hz)	5
Missile Trajectory (XY Plot)	X-min X-Max	0, 10000
	Y-Min Y-Max	0, 10000
Autopilot	PNo	3
	PN max	6
	PN min	1
Airframe	Velocity (m/s)	279
	X Position (m)*	0
	Y Position (m)*	0
	Heading (Deg)*	45
	Max Latax (g)	4
	Missile: Wing Span (m)	1
	Missile: Average Wing Chord (m)	0.5
	Missile: Length (m)	4.69
	Missile: Mass (kg)	655
	Missile: Diameter (m)	0.35
	Warhead Mass (kg)	70
	Cruise Altitude (m)	15

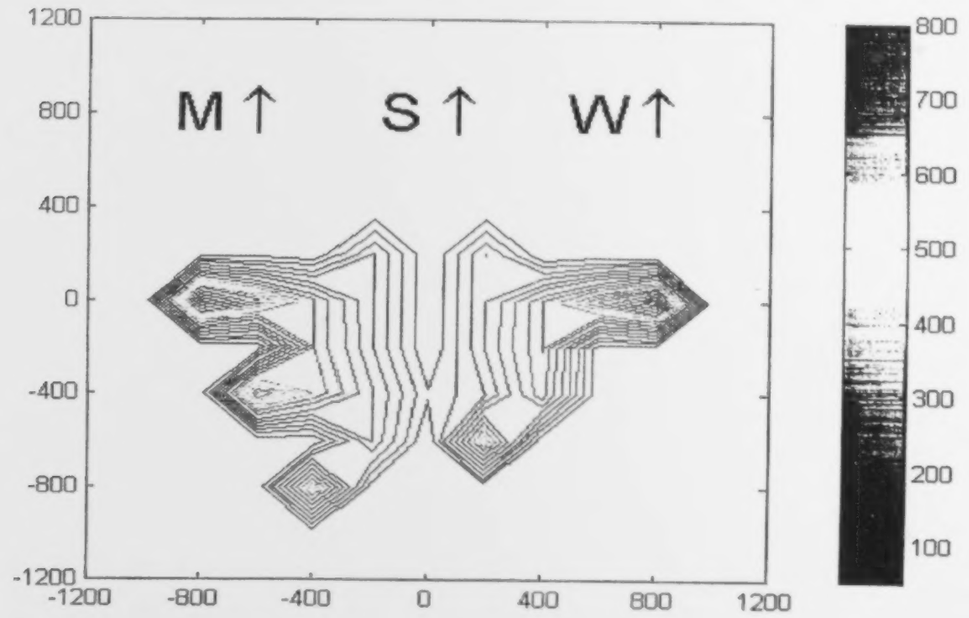

Figure 3. Miss Distance as a Function of Chaff Position for Ship Heading North

Miss distances are plotted at the initial chaff positions measured in metres from the position of the ship, x=0 y=0.75, at chaff launch. The missile and ship were heading north, or up, along the Y-axis and the wind was blowing towards the north. The contour interval is 50 m, the smallest enclosed areas are the highest contours and miss distances outside the 50 m contour are less than 50 m.

Several minor explorations were carried out to explain why the chaff was found initially to be much more effective on one side of the ship than the other. These erroneous results are not shown here. The seeker's direction of initial range and angle search were not found to be responsible in that they had little effect on the effectiveness of chaff for most chaff positions. While trying to explain the strong asymmetry, power densities in the range gate, range gate position and missile heading and missile position, with respect to the ship, were examined. The missile seeker's beam width, half-power at 5.7 degrees, was large enough to encompass the chaff on either side of the ship. Further analysis showed that, when the missile was not at the origin, the range gate was at the wrong position within the seeker model. To correct this error, the developer modified the simulation code to Version 1.3 and the simulations were rerun.

Figure 3 shows the effectiveness of chaff placed at ranges up to 1.2 km from the ship for bearings between 0 and 360 degrees relative to the ship heading. For each simulation chaff was placed at one of the positions on a 200-m grid covering the chaff deployment region and the miss distance was calculated with the simulation software. This was repeated until miss distances had been determined for chaff deployments at all of the grid points. We chose this chaff deployment region rather than one restricted to a particular launcher in order to determine the nature of the effectiveness of the chaff without being restricted by the launcher. This approach allows the effect of the missile seeker parameters to be seen in the results obtained. Since the seed for RCS fluctuations is the same for all simulations only one instance of the effect of RCS variability is captured. To obtain the mean response with an order of magnitude reduction in uncertainty, for the scenario investigated in this report, would extend the simulation time from eight days on a Pentium 450 to 800 days.

From Figure 3 it can be seen that the miss distance approximates the distance between the chaff and the ship in the region of chaff effectiveness, as would be expected if the simulation is correct. The figure is somewhat symmetric which is consistent with the near symmetry of the scenario. Note that there is some asymmetry in the model in that the azimuthal search is to the left during reacquisition. Individual engagements from Figure 3 were examined to determine why chaff closer to the missile than the ship on the left side is more effective than chaff on the right side. It was found that there were a series of mode changes before the missile locked onto the chaff or ship. The position and size of the clutter gate are important factors in determining whether mode changes occur. The size of the clutter gate itself depends on the search mode. In summary the chaff deployed 400, 600 and 800 m towards the missile was effective because the clutter gate included the chaff and put the seeker in search mode. The initial search to the left in azimuth made the chaff to the left more effective. This would be the case for a missile with a single clutter gate.

If the initial search direction is changed from search to the left to search to the right, during reacquisition, then the chaff effectiveness plot equivalent to Figure 3 is a reflection of Figure 3 about the Y-axis. This and examination of individual engagements validated the consistency of the code over numerous simulations where there are often several search mode changes and shows the code to be precisely consistent. The code was also consistent with the intended design.

It would be very helpful to have the range gate and clutter gates displayed on the x-y engagement so that the missile engagement could be followed without having to resort to a time consuming detailed examination of the oscilloscope outputs. This is especially important when hundreds of individual engagements need to be examined.

The ineffectiveness of chaff further from the missile than the ship is the result of the positioning of the clutter gate, the chaff being outside the range gate and the fact that chaff and ship are moving in the same direction. In producing Figure 3 the clutter gate was positioned between the missile and the ship. When the clutter gate was positioned beyond the ship the chaff

was also found to be effective if deployed further from the missile than the ship. This is simply a matter of the clutter gate measurement producing a high threshold from the chaff in the gate.

There is a third seeker parameter that affects the symmetry of the chaff effectiveness pattern. All the figures presented correspond to a seeker receiver processor for which the initial search during acquisition is out in range i.e. in the direction of the missile heading. The search direction in range was changed from out to in, i.e. opposite to the direction of the missile heading and all other parameters were as for the conditions of Figure 3. Under this condition the chaff effectiveness equivalent to Figure 3 becomes symmetric with the right half a reflection of the left half about the Y-axis. The search to closer ranges is better at finding the chaff in the lower right quadrant than the search out in range because the left to right angle search offsets the range gate to the left.

Detailed examination of engagements for the symmetric pattern shows that the process consists of multiple searches and acquisitions. The reason given above for the symmetry is a necessary but not sufficient condition. The pattern is also a function of the seeker beam shapes since it is first necessary that the chaff appear in the clutter gate, which in itself would lead to a symmetric result.

The investigation of the reason for the symmetry and asymmetry revealed that the simulation followed the conceptual model. Thus the chaff effectiveness is in agreement with the conceptual model.

There are two parts to Figure 3, the region within 150 m of the ship at time of chaff launch and the region between -150 and -800 m measured along the line of sight from the missile to the ship. In the upper region the chaff falls in the range gate and seduces the missile over most of the region. In the lower region the chaff initially falls outside the range gate but at a later time is within the clutter gate so that the threshold is raised and track on the ship is lost. When reacquisition is commenced, the chaff seduces the missile. This often involves several mode changes before the end of the engagement. When examined at finer resolution the width of the upper region, in range from the missile, was confirmed to be the 300-m width of the wide range gate. The overall width in azimuth of the effective chaff region, approximates the null to null transmit and receive beam widths. Thus the chaff will be acquired if it lies within the range gate and well within the first nulls to the left and right in the antenna pattern, about 7 degrees or 1200 m on either side of initial boresight at a missile range of 9.9 km. Simulation showed that the chaff was ineffective beyond the furthest range of the wide range gate and beyond the null to null width. Consequently simulations were restricted to the wide range gate within the null to null width of the seeker lobe.

The linear contour segments in Figure 3 at large ranges from the ship are a result of the sparse sampling in range and bearing. At very small ranges the miss distance approximates the distance between chaff and ship as expected, however, because the miss distance can even vary over the 75 m width of the narrow range gate, finer sampling is required to determine the miss distance in this region. Despite coarse sampling and the low resolution of the miss-distance

contours, there is a clear indication of a more than 50-m wide corridor near the ship where the miss distance is less than 50 m. This feature was found to exist when a finer spatial resolution analysis was carried out. The corridor represents the ineffectiveness of chaff launched near the ship's azimuth as seen by the missile. Such chaff does not lead to large miss distances because the chaff remains near the ship.

Sometimes both chaff and ship may lie in the range gate till the missile is half way to the ship and to have similar levels in the range gate. Under this condition the missile is guided to a point midway between chaff and ship. Later in the engagement, when the chaff RCS declines as a result of fluctuations that persist for a long enough period, the tracker acquires the ship.

If the miss-distances are evaluated on a finer grid for the scenario in Figure 3, miss distances of less than 50 m are found for chaff ranges up to 400 m from the ship's position at the time of chaff launch. This occurs for chaff in the range gate. These occur at bearings of 60 degrees on either side of the ship's heading. Examination of simulation input and output parameters, for these positions, shows that initially the chaff seduces the missile but that the wind drifts the chaff in such a direction that the narrow tracking range gate again includes the reflection from the ship. The level of the reflection from the ship exceeds the chaff level for a sufficient duration that the missile reacquires the ship and the chaff falls out of the range gate. This provides a clear indication that finer sampling is required to find islands where chaff is ineffective within regions where chaff is effective.

In Figure 3 there are large areas in which chaff appears to be effective. For some of these regions there are probably areas where finer analysis will show regions where chaff is ineffective as described in the previous paragraph.

The effectiveness of chaff is probably robust with respect to deployment position; i.e. small changes in chaff position would only lead to small changes in miss-distance for most of the region where chaff is effective in Figure 3. On account of the scenario analysed and physics of the problem such robust regions are likely but it is necessary to use a finer resolution in the chaff position to define these regions.

The results presented in Figure 3 required 145 simulations. To reduce simulation time all oscilloscope displays and the XY-display in CJASCM were suppressed. The 145 simulations took about seven hours to compute on a Pentium that had 64 megabytes of memory and a clock speed of 133 MHz. Execution times were confirmed to be approximately inversely proportional to clock speed for clock speeds up to 450 MHz. For CJASCM a further increase in random access memory size will not produce a speedup because only 64 megabytes are required during execution. With all displays enabled during the simulation execution time is doubled.

An exhaustive simulation of chaff effectiveness over the parameters of the problem, on a fine scale to find small regions where chaff is ineffective, would require a considerable number of computations. Consider the evaluation of chaff effectiveness as a function of six parameters. If the effectiveness is evaluated for only ten values of these parameters then a million simulations

are required. At this coarse resolution the simulation runs would take about two years and would increase dramatically if finer resolution or additional EW countermeasures were considered. The time required when using CJASCM could be reduced by a factor of ten by converting CJASCM to C. This is about twice as cost effective as purchasing ten PC's provided that the Matlab code generator can translate CJASCM and that CJASCM includes a batch and database capability. These issues are under investigation with positive results to date.

No catastrophic code failure was experienced for all 11,601 simulations required in producing the figures in this document. At the time of writing, in associated investigations 100,000 simulations ran to completion without any difficulty being flagged, attesting to the reliability of the code. When individual engagements were examined to explain what appeared to be anomalous results the results were found to be consistent with the conceptual model. This increases user confidence in using the code for what it was designed to do. Limitations encountered point to the desirability of developing the code to include a GUI for batch mode, plots of miss-distance for a variety of parameter pairs and for developing a coherent relational database for input and output files. The database manager and front end for the software now under development by TTI should meet all of these needs.

4.2.1 Effect of Wind Direction on Chaff Effectiveness

The exercise of investigating the effect of wind direction on chaff is intended to reveal some of the capabilities of CJASCM 1.2. While no further physical modelling or programming anomaly was found in this phase several improvements from the user's point of view were identified. When setting up batch runs, and when investigating anomalies by examining single simulations in detail, it is easy to get confused regarding directions. This arises because two different conventions have to be taken into consideration, namely the convention for ship navigation and the Matlab or mathematical convention. For navigation positive angles are measured as clockwise from north while for Matlab positive angles are measured anti-clockwise from the X-axis which is east in this study. Tracking multiple runs would also be aided by parameter archiving which can be done by using a database. The developer is presently developing such a capability by adding a Microsoft Access front end. This new front end should also enable multiple runs and the display of results for easily specified parameter ranges.

Figure 4 shows a compilation of miss distances for missile seduction by chaff for the same scenario as for Figure 3 except that the wind direction is varied from subfigure to subfigure. The subfigures have on the whole a general symmetry about the missile heading as in Figure 3.

The results demonstrate that chaff would be consistently ineffective when deployed in over 60 % of the deployment region shown in each subfigure in Figure 4. On the other hand the regions where the chaff is shown to be most effective, regardless of wind direction, is consistently found to be at ranges between 75 m and 1200 m from the ship. These regions are located in opposing directions from the ship, perpendicular to a line joining the initial position of ship and missile. Both ship motion and wind must be considered when explaining the subfigures. Relative motion between ship and chaff makes chaff more effective where the

separation between chaff and ship changes slowly so that the missile has sufficient time to be seduced by the chaff. Wind blowing across the ship reduces the effectiveness of the chaff on the windward side. The explanations given for Figure 3 apply here but with modifications as a result of the changing wind direction. Most noticeable is the effectiveness of chaff initially near or over the ship but blown across the ship and resulting in a seduction of the missile. Thus the corridor of small miss distances that parallels the missile's line of sight is displaced in the opposite direction to the component of the wind across the ship.

The slow variation of miss-distance with wind direction indicates that a much finer examination of miss-distance with wind direction is not likely to yield very different results for most wind directions. For the scenario investigated we may conclude that the use of chaff for seduction is probably fairly robust in that a small change of wind direction will not render the tactic for that wind direction ineffective. Thus a carefully chosen set of tactics for say every ten degrees change in wind direction will probably provide a robust set of practical tactics for the scenario studied.

The miss distances are on the whole somewhat less satisfactory when the wind heading is at 45 degrees to either side of the ship's heading. For these wind directions there are small regions where the chaff is most effective. The reason is much the same as discussed in connection with Figure 3 where the chaff is ineffective at bearings of 60 degrees on either side of the ship's heading. The wind drifts the chaff so that at some time during the engagement the narrow tracking range gate falls over the ship. During this period the ship's skin return exceeds the chaff return so the tracker centres on the ship and before a stronger chaff signal is again present the chaff return falls out of the narrow range gate. Remember that the chaff and ship RCS are modelled as Rayleigh distributed in time. The result is small miss distances interspersed with large miss distances for these wind directions. In this study since we have not investigated the stochastic effect of variation in RCS from one realisation to the next. This will not have a profound effect at high chaff to ship RCS ratios. Even at low ratios the modelling of variable RCS in time will have captured a single realisation of the effect of statistical variations on the effectiveness of chaff. Because including stochastic modelling increases the computational load by at least an order of magnitude, it would be best to limit the analysis to a specific chaff deployment system and specific tactics before including stochastic effects to evaluate the variance of the miss distance function.

There is also a clear indication that the miss distance for chaff in the corridor along which the missile is travelling is consistently small, no matter what the wind direction is. Thus such deployments are counterproductive.

4.2.2 Effect of the Missile Heading on Chaff Effectiveness

In Figures 4 to 8 inclusive the effect of the missile heading relative to the ship on chaff effectiveness is investigated for all sixteen wind-directions. When the same subplot is compared among the subfigures of Figures 4 to 8, for different ship headings, some features remain and some change substantially. Chaff deployed between 50 and 1200 m to either side of a line

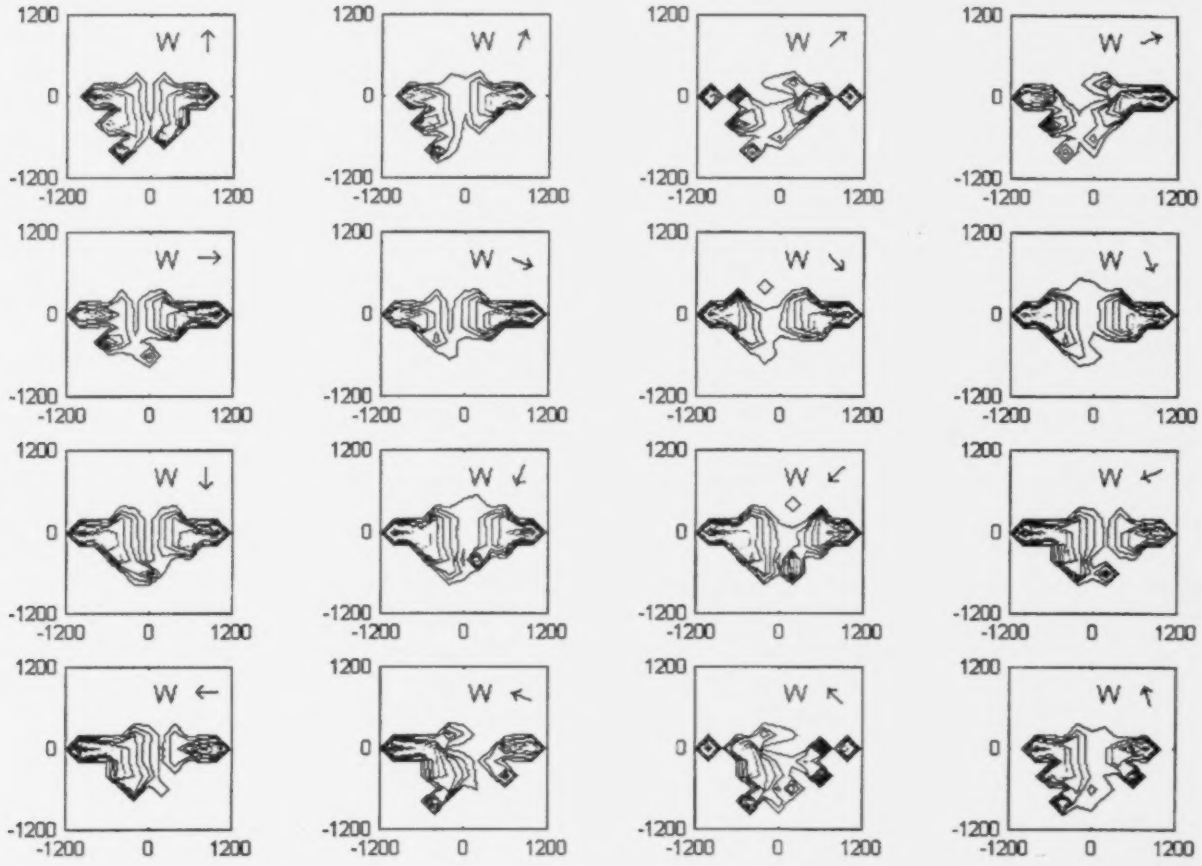

Figure 4. Miss Distance as a Function of Chaff Position and Wind Direction for Ship Heading North

Miss distances are plotted at the initial chaff positions measured in meters from the position of the ship, x=0 y=7.5 m, at chaff launch. The missile and ship were heading north, or up, along the Y-axis. The contour interval is 100 m, starting at 50 m, with the smallest enclosed area the highest contour. The direction towards which the wind blows (W) is shown as an arrow, with 22.5-degree increments between subfigures.

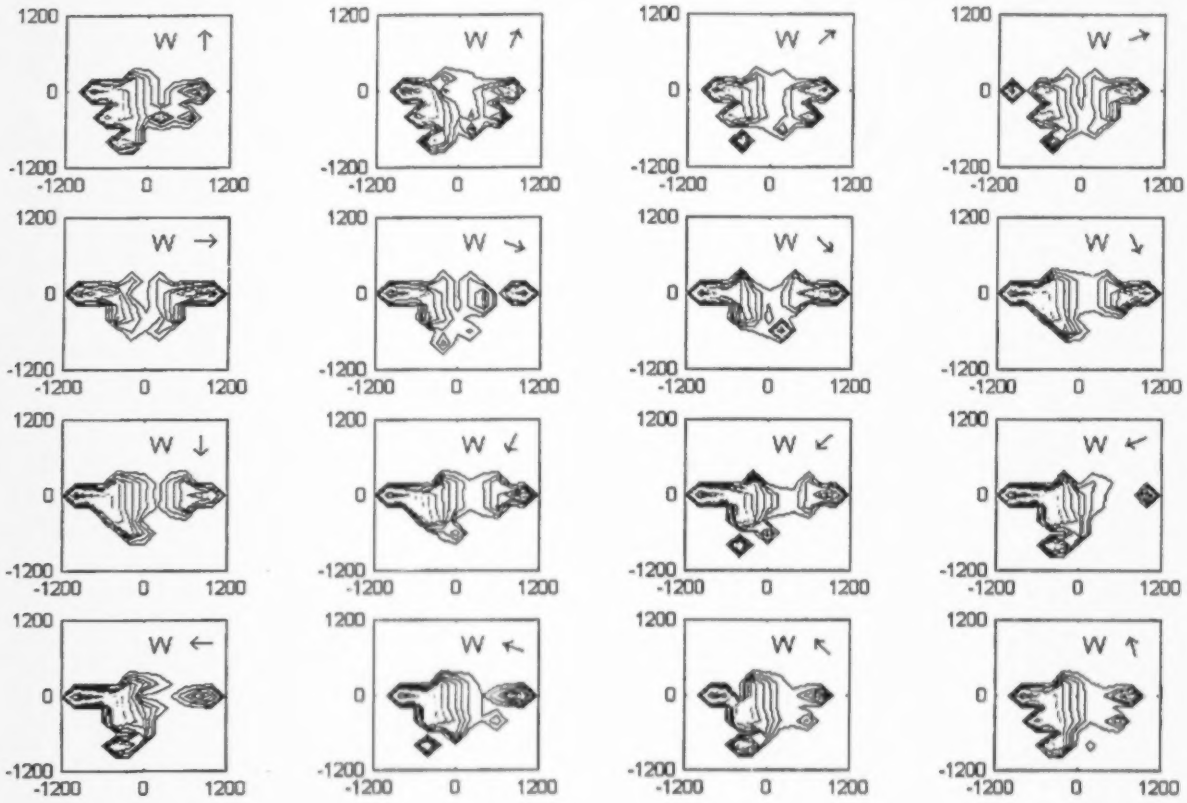

Figure 5. Miss Distance as a Function of Chaff Position and Wind Direction for Ship Heading Northeast

Miss distances are plotted at the initial chaff positions measured in meters from the position of the ship at chaff launch. The missile was heading north, or up, along the Y-axis and the ship heading was 45 degrees clockwise from north. The contour interval is 100 m, starting at 50 m, with the smallest enclosed area the highest contour. The direction towards which the wind (W) blows is shown as an arrow, with 22.5-degree increments between subfigures.

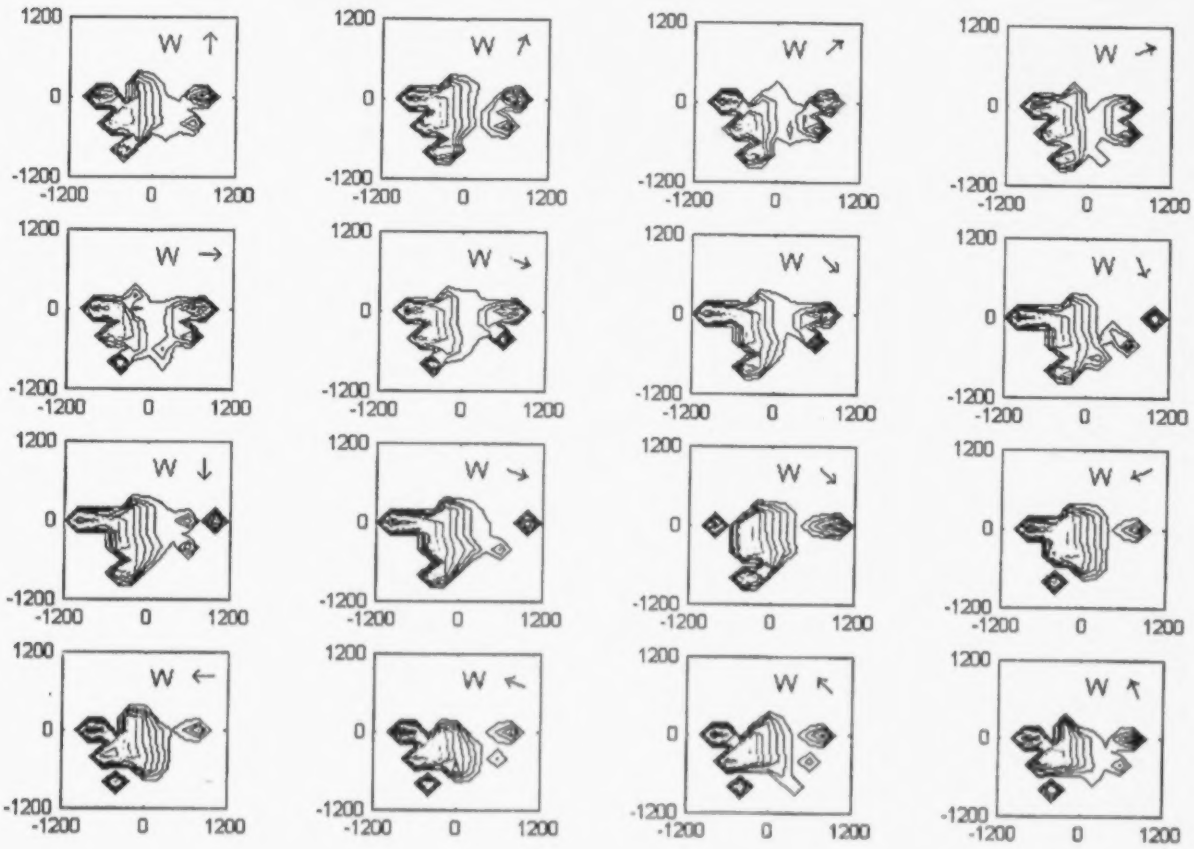

Figure 6. Miss Distance as a Function of Chaff Position and Wind Direction for Ship Heading East

Miss distances are plotted at the initial chaff positions measured in meters from the position of the ship at chaff launch. The missile was heading north, or up, along the Y-axis and the ship heading was 90 degrees clockwise from north. The contour interval is 100 m, starting at 50 m, with the smallest enclosed area the highest contour. The direction towards which the wind (W) blows is shown as an arrow, with 22.5-degree increments between subfigures.

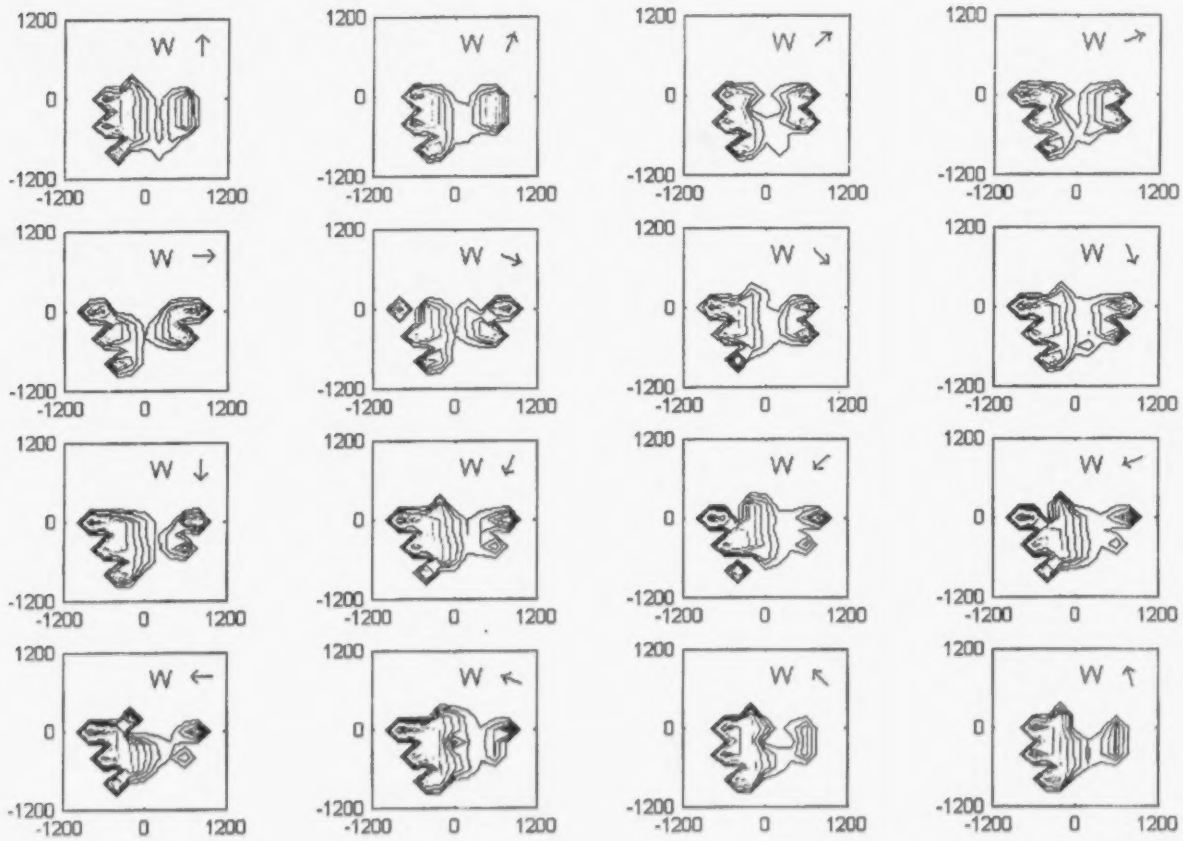

Figure 7. Miss Distance as a Function of Chaff Position and Wind Direction for Ship Heading Southeast

Miss distances are plotted at the initial chaff positions measured in meters from the position of the ship at chaff launch. The missile was heading north, or up, along the Y-axis and the ship heading was 135 degrees clockwise from north. The contour interval is 100 m, starting at 50 m, with the smallest enclosed area the highest contour. The direction towards which the wind (W) blows is shown as an arrow, with 22.5-degree increments between subfigures.

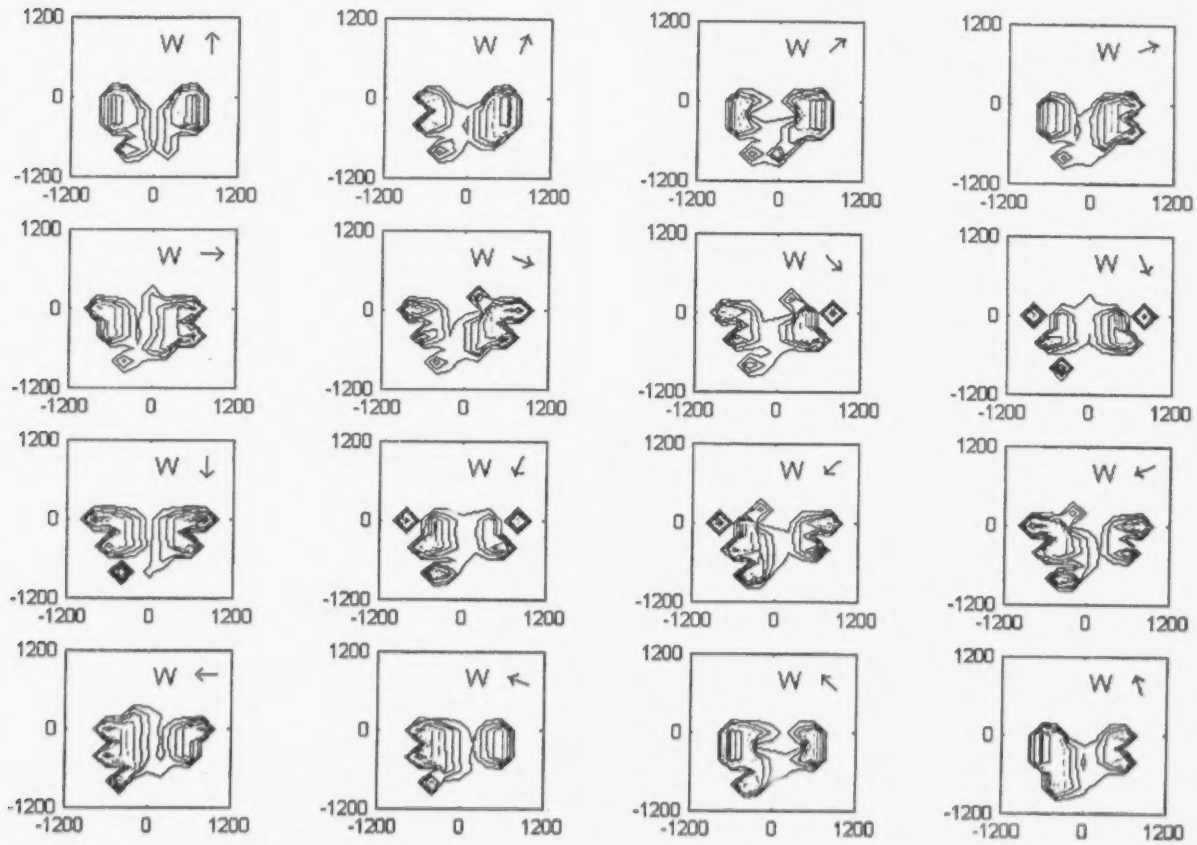

Figure 8. Miss Distance as a Function of Chaff Position and Wind Direction for Ship Heading South

Miss distances are plotted at the initial chaff positions measured in meters from the position of the ship at chaff launch. The missile was heading north, or up, along the Y-axis and the ship heading was 180 degrees clockwise from north. The contour interval is 100 m, starting at 50 m, with the smallest enclosed area the highest contour. The direction towards which the wind (W) blows is shown as an arrow, with 22.5-degree increments between subfigures.

through missile and ship in the vicinity of the ship remains most effective in seducing the missile. The largest region of chaff effectiveness is the one that includes the chaff deployed downwind. The shape of this region is modified for the different missile and ship headings as can be seen from Figures 4,5,6,7 and 8. As discussed in connection with Figure 3 the size, position and the area for effective deployment of chaff reflects the width of the range gate and the decreasing area covered by the seeker lobe during the engagement. Since these results are as expected for the parameter values of the scenario they validate the code in the range gate, seeker and tracker modules. Furthermore the guidance model is shown to be effective in that the missile homes on the target found by the seeker. The subplots also exhibit a smooth transition as parameters are changed which is a characteristic of realistic physical models.

In examining Figures 4 to 8 inclusive there appear to be broad regions where the chaff is effective for seduction or distraction. A finer resolution analysis is required to determine whether there are areas within these regions for which chaff is ineffective. The time required prevented us from carrying out such a fine analysis at this time.

The results presented represent the effect of the same realisation of random variations of RCS for each simulation. If the simulations are rerun for another realisation of the scintillation statistics the engagement will usually turnout to have a smaller or larger miss distance. For the simulations in this study the results presented would only change the appearance of the contour plots in Figures 4 to 8 in detail. The study of the effect of random variations is the subject of a separate investigation.

Further investigation would be required to determine how the miss distance performance would change with the wind speed, ship speed and other parameters. This would require considerably more simulations. Thus, while it may take too long to predict the outcome of an engagement during an engagement, with present day software, it may be feasible to build an extensive lookup table, using CJASCM or similar EW software, from which to quickly select a robust and successful tactic.

EW software could be employed in simulations to identify appropriate engagement tactics to ensure large miss-distances. In such an approach the miss-distance is determined in a systematic manner to identify likely tactics. Monte Carlo simulations are carried out and analysed to identify regions in multidimensional parameter space for which chaff deployment produces adequate miss-distances for ranges of several parameter values. For some scenarios the time required exceeds the age of the universe. For restricted scenarios the use of CJASCM is feasible because of the modest execution time per simulation. An order of magnitude reduction is also possible by translating the code to C and further reductions in total time required for the study can be achieved through some level of networked computers.

5.0 SUMMARY OF AREAS FOR DEVELOPMENT

The software error in which the line of sight from the missile to the ship was miscalculated was addressed immediately in producing CJASM13 and no longer presents a risk. Unfortunately unidentified software errors that do not affect the outcome in a frequent or noticeable way may still exist, as is usually the case in most software. Thus one must constantly watch out for anomalous results to ensure that any such limitations are identified. In making comparisons with data one should also keep in mind that experimental trial data is also to be treated with caution. Some of the areas in which CJASCM might be enhanced are outlined below.

5.1 Signal-to-Noise Ratio

In the CJASCM developer's documents signal-to-noise ratio has not been discussed in detail for the end-to-end simulation. Neither has it been tracked through the simulation code in any detail in the validation process. Thus the signal-to-noise ratio at various stages in the simulation must be investigated to verify that propagation loss, antenna gain and tracking gain are correctly modelled.

5.2 Extension to Multiple Ships and Missiles

TESS includes CJASCM as a simulation of one missile against one ship. At the time of writing, the feasibility of having the user add additional ships, chaff clouds or missiles to the simulation in a timely manner has not been investigated. It is possible for the end user to reuse modules but does require expertise to interface the modules with other modules since the self documenting level of Simulink may be less than adequate for interfacing. In order to have the code run efficiently, a few-on-few model could be developed with the user selecting the number of ships or decoys at run time. This can be achieved by having 'enable' functions associated with each ship or decoy. A configuration that is specific to a particular number of ships and missiles can then be selected prior to execution or compilation. If this issue is investigated and code can be developed in this way, then the utility of the TESS suite for this purpose would be enhanced considerably.

5.3 Further Validation and Debugging

Comparison of CJASCM predictions with results from validated codes and possibly from field trials would further validate the code. This process would require a substantial effort if all components were to be validated. Validated Simulink modules from other sources might also be used to replace components in CJASCM.

5.4 Scintillation Statistics

As discussed in section 3.3, the statistics of the RCS of objects were not those intended in the conceptual model. A bias was introduced to correct this discrepancy. Since the bias depends

on the correlation it should be determined as a function of correlation time, possibly by using a lookup table. A better solution would be to remove the discrepancy between the intended and modelled mean RCS by correcting or replacing the Matlab block. The developer is presently addressing this issue.

5.5 User Interface and Database

CJASCM could be enhanced by the addition of a relational database capability to keep track of input parameters and output files. This is especially important when making multiple runs. The developer plans to use Microsoft Access for the purpose and to provide a user interface for handling batch mode and for plotting of results from multiple runs. These features are to be added to the three-dimensional version.

5.6 Code Enhancements

All of the models used in CJASCM could be enhanced either by adding more realistic details or by providing a variety of models. This could be done through collaboration with other laboratories, which require similar models, such as Defence Research Establishment Valcartier. Enhancing CJASCM would likely continue as long as there is an interest in using CJASCM.

6.0 CONCLUDING REMARKS

Some CJASCM modules are sufficiently realistic that ultimately CJASCM could, after further development, be used to evaluate methods of identifying electronic warfare tactics. The further development would include validation of models of realistic threats including a six degree of freedom model of missile flight and a three-dimensional model of seeker lobes. CJASCM and presumably other TESS simulations could also be used in investigations of the feasibility of developing an EW Control Processor and to investigate Sensors and Weapons Systems Integration. Parallel execution of CJASCM on multiple CPUs would extend the possible applications to include an investigation of real-time EW and real-time Sensors and Weapons control. If CJASCM is to be used for these simulations it will be necessary to convert Simulink into C code in order to reduce execution time. This would demonstrate the rapid prototyping of real-time EW systems in a cost-effective manner consistent with available resources. Both hardware and software would be cost effective and therefore lend themselves to collaboration and marketing.

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(U) The 2D chaff and jamming effectiveness simulator for anti-ship cruise missile engagements, CJASCM, is currently under development under a Defence Industrial Research (DIR) contract. CJASM was rapidly prototyped in the fifth generation language Simulink which itself is built on Matlab and is therefore modular and open to modification to a few on few model from the present one-on-one model. DREO provided Beta testing of CJASCM as agreed under the DIR contract and carried out the limited validation described here. Numerous simulations of chaff effectiveness as a function of chaff position, missile headin g and wind heading, confirmed that the simulations followed the conceptual model as summarized in this document and that the code was robust. The present simulation can be used for training purposes and for investigating ways of identifying chaff decoy tactics. In order to use the code for developing precise electronic warfare tactics for a one-on-one engagement, further validation and development of the overall simulation and the modules comprising the simulation will be required. Enhancements, such as conversion to 3-D and the inclusion of a relational database to archive simulation input and output, are already planned in the time remaining under the DIR. At the completion of the present DIR grant further development and validation will be required if CJASCM is to be used for tactics generation. The extent of these enhancements will depend on the scenarios under investigation. On account of the open nature of the software, extension to new countermeasures equipment and missiles should remain feasible.

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